

EVALUATION OF p + 40Ca CROSS SECTIONS FOR THE ENERGY  
RANGE 1.0 to 150 MeV

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This evaluation provides a complete representation of the nuclear data needed for transport, damage, heating, radioactivity, and shielding applications over the incident proton energy range from 1 to 150 MeV. Production cross sections and emission spectra are given for neutrons, protons, deuterons, tritons, alpha particles, gamma rays, and all residual nuclides produced ( $A > 5$ ) in the reaction chains.

To summarize, the ENDF sections with non-zero data are:

MF=3 MT= 2 Integral of nuclear plus interference components of the elastic scattering cross section

MT= 5 Sum of binary ( $n, n'$ ) and ( $n, x$ ) reactions

MF=6 MT= 2 Elastic angular distributions given as ratios of the differential nuclear-plus-interference to the integrated value.

MT= 5 Production cross sections and energy-angle distributions for emission neutrons, protons, deuterons, and alphas; and angle-integrated spectra for gamma rays and residual nuclei that are stable against particle emission

The evaluation is based on nuclear model calculations that have been benchmarked to experimental data. We use the GNASH code system (Yo92), which utilizes Hauser-Feshbach statistical, preequilibrium and direct-reaction theories. Spherical optical model calculations are used to obtain particle transmission coefficients for the Hauser-Feshbach calculations, as well as for the elastic neutron angular distributions.

Cross sections and spectra for producing individual residual nuclei are included for reactions that exceed a cross section of approximately 1 nb at any energy. The energy-angle-correlations for all outgoing particles are based on Kalbach systematics (Ka88).

A model was developed to calculate the energy distributions of all recoil nuclei in the GNASH calculations (Ch96a). The recoil energy distributions are represented in the laboratory system in MT=5, MF=6, and are given as isotropic in the lab system. All other data in MT=5, MF=6 are given in the center-of-mass system. This method of representation utilizes the LCT=3 option approved at the November, 1996, CSEWG meeting..

The starting point for this evaluation was the previous Livermore (1995) evaluation by Chadwick and Young for neutrons up to 100 MeV [Ch95], and protons up to 250 MeV [Ch96b]. The main additions in the current work were: (1) Extension of the neutron calculations to higher energies; (2) Inclusion of direct inelastic scattering to low-lying collective states using ECIS; (3) inclusion of a renormalization of the calculated results to circumvent a numerical inaccuracy at higher incident energies ( $> 150$  MeV) which ensure the individual reactions sum to the evaluated nonelastic cross section; (4) inclusion of  $A > 4$  nuclide

production and nuclide energy spectra; (5) inclusion of triton emission; and (6) utilization of ENDF-6 format.

The neutron total cross section was evaluated from available experimental data. The evaluation was based primarily on Finlay's 1993 high-accuracy measurements [Fi93].

The optical potential of Islam [Is88] specially developed for n+Ca elastic scattering, was used for neutrons from 20 to 60 MeV, and above this energy the Madland global potential was used [Ma88]. The Wilmore-Hodgson potential was used for neutrons below 20 MeV [Wi64]. For incident protons, the Islam neutron potential was modified to account for proton scattering from 20 to 60 MeV, and again the Madland global potential was used at higher energies. The Becchetti-Greenlees potential was used for protons below 20 MeV [Be69]. For deuterons, tritons and alphas the method of Watanabe, which uses a modified Perey potential [Pe63], was applied at all energies [Ma88].

Direct inelastic scattering to the low-lying collective states was calculated with the ECIS code. Deformation lengths were taken from the works of Alarcon and Rapaport [8] and Honore et al. [Ho86], giving: 3- (Ex= 3.736 MeV, delta=1.340), 2+ (Ex=3.904, delta=0.360), and 5- (Ex=4.492, delta=0.930).

While the above optical potentials did describe the experimental neutron and proton nonelastic cross section data fairly well, we modified these theoretical predictions slightly to better agree with the measurements, and renormalized the transmission coefficients accordingly. The calculated neutron elastic scattering distributions agree well with experimental data.

Nuclear level densities were taken from the Ignatyuk model [Ig75], which includes a washing out of shell effects with increasing excitation energy, and gamma-ray strength functions were obtained from the model of Kopecky and Uhl [Ko90].

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20040 = TARGET 1000Z+A (if A=0 then elemental)

1001 = PROJECTILE 1000Z+A

Nonelastic, elastic, and Production cross sections for A&lt;5 projectiles in barns:

Energy	nonelas	elastic	neutron	proton	deuteron	triton	helium3	alpha	gamma
5.000E+00	4.526E-02	0.000E+00	0.000E+00	4.526E-02	0.000E+00	0.000E+00	0.000E+00	0.000E+00	4.534E-02
6.000E+00	1.652E-01	0.000E+00	0.000E+00	1.652E-01	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.801E-01
7.000E+00	3.817E-01	0.000E+00	0.000E+00	3.816E-01	0.000E+00	0.000E+00	0.000E+00	5.804E-10	4.549E-01
8.000E+00	5.280E-01	0.000E+00	0.000E+00	5.280E-01	0.000E+00	0.000E+00	0.000E+00	1.662E-06	7.208E-01
9.000E+00	6.318E-01	0.000E+00	0.000E+00	6.317E-01	0.000E+00	0.000E+00	0.000E+00	8.038E-05	1.016E+00
1.000E+01	7.031E-01	0.000E+00	0.000E+00	7.012E-01	0.000E+00	0.000E+00	0.000E+00	1.893E-03	1.274E+00
1.100E+01	7.494E-01	0.000E+00	0.000E+00	7.479E-01	0.000E+00	0.000E+00	0.000E+00	5.635E-03	1.467E+00
1.200E+01	7.827E-01	0.000E+00	0.000E+00	8.135E-01	0.000E+00	0.000E+00	0.000E+00	1.043E-02	1.551E+00
1.300E+01	8.079E-01	0.000E+00	0.000E+00	9.365E-01	0.000E+00	0.000E+00	0.000E+00	1.429E-02	1.450E+00
1.400E+01	8.279E-01	0.000E+00	0.000E+00	1.085E+00	0.000E+00	0.000E+00	0.000E+00	1.722E-02	1.243E+00
1.500E+01	8.384E-01	0.000E+00	0.000E+00	1.217E+00	4.674E-07	0.000E+00	0.000E+00	2.438E-02	1.003E+00
1.600E+01	8.410E-01	0.000E+00	5.548E-04	1.293E+00	2.431E-05	0.000E+00	0.000E+00	3.553E-02	8.379E-01
1.700E+01	8.423E-01	0.000E+00	1.626E-03	1.338E+00	2.992E-04	0.000E+00	0.000E+00	5.113E-02	7.494E-01
1.800E+01	8.425E-01	0.000E+00	3.566E-03	1.363E+00	1.219E-03	0.000E+00	0.000E+00	6.837E-02	7.326E-01
1.900E+01	8.412E-01	0.000E+00	6.692E-03	1.375E+00	2.941E-03	0.000E+00	0.000E+00	8.224E-02	7.725E-01
2.000E+01	8.429E-01	0.000E+00	1.117E-02	1.386E+00	5.302E-03	0.000E+00	0.000E+00	9.228E-02	8.234E-01
2.200E+01	8.579E-01	0.000E+00	2.352E-02	1.408E+00	1.200E-02	1.316E-10	0.000E+00	1.065E-01	1.015E+00
2.400E+01	8.733E-01	0.000E+00	3.707E-02	1.441E+00	1.869E-02	7.048E-07	0.000E+00	1.168E-01	1.204E+00
2.600E+01	8.870E-01	0.000E+00	5.431E-02	1.494E+00	2.611E-02	1.038E-05	0.000E+00	1.245E-01	1.273E+00
2.800E+01	8.902E-01	0.000E+00	7.415E-02	1.545E+00	3.298E-02	4.761E-05	0.000E+00	1.324E-01	1.247E+00
3.000E+01	8.800E-01	0.000E+00	9.578E-02	1.571E+00	3.894E-02	2.211E-04	0.000E+00	1.390E-01	1.171E+00
3.500E+01	8.459E-01	0.000E+00	1.525E-01	1.582E+00	4.765E-02	3.917E-04	0.000E+00	1.463E-01	1.089E+00
4.000E+01	8.120E-01	0.000E+00	2.018E-01	1.562E+00	5.456E-02	7.017E-04	0.000E+00	1.407E-01	1.065E+00
4.500E+01	7.820E-01	0.000E+00	2.496E-01	1.551E+00	5.727E-02	1.007E-03	0.000E+00	1.384E-01	1.001E+00
5.000E+01	7.550E-01	0.000E+00	2.935E-01	1.549E+00	5.860E-02	1.264E-03	0.000E+00	1.390E-01	9.657E-01
5.500E+01	7.280E-01	0.000E+00	3.339E-01	1.549E+00	5.754E-02	1.540E-03	0.000E+00	1.426E-01	9.282E-01
6.000E+01	7.060E-01	0.000E+00	3.704E-01	1.555E+00	5.771E-02	1.801E-03	0.000E+00	1.478E-01	8.951E-01
6.500E+01	6.847E-01	0.000E+00	4.080E-01	1.567E+00	5.739E-02	2.085E-03	0.000E+00	1.570E-01	8.711E-01
7.000E+01	6.640E-01	0.000E+00	4.373E-01	1.569E+00	5.783E-02	2.357E-03	0.000E+00	1.622E-01	8.296E-01
7.500E+01	6.461E-01	0.000E+00	4.692E-01	1.571E+00	5.750E-02	2.661E-03	0.000E+00	1.651E-01	8.154E-01
8.000E+01	6.310E-01	0.000E+00	5.042E-01	1.582E+00	5.793E-02	2.999E-03	0.000E+00	1.693E-01	7.897E-01
8.500E+01	6.170E-01	0.000E+00	5.424E-01	1.603E+00	5.768E-02	3.459E-03	0.000E+00	1.772E-01	7.742E-01
9.000E+01	6.041E-01	0.000E+00	5.726E-01	1.611E+00	5.826E-02	3.886E-03	0.000E+00	1.803E-01	7.570E-01
9.500E+01	5.926E-01	0.000E+00	6.026E-01	1.622E+00	5.897E-02	4.364E-03	0.000E+00	1.839E-01	7.442E-01
1.000E+02	5.830E-01	0.000E+00	6.321E-01	1.636E+00	5.979E-02	4.871E-03	0.000E+00	1.880E-01	7.322E-01
1.100E+02	5.679E-01	0.000E+00	6.946E-01	1.675E+00	6.201E-02	6.192E-03	0.000E+00	1.960E-01	7.140E-01
1.200E+02	5.570E-01	0.000E+00	7.507E-01	1.708E+00	6.414E-02	7.594E-03	0.000E+00	2.018E-01	6.986E-01
1.300E+02	5.486E-01	0.000E+00	8.088E-01	1.748E+00	6.654E-02	9.309E-03	0.000E+00	2.103E-01	6.876E-01
1.400E+02	5.420E-01	0.000E+00	8.584E-01	1.785E+00	6.907E-02	1.104E-02	0.000E+00	2.154E-01	6.751E-01
1.500E+02	5.372E-01	0.000E+00	9.029E-01	1.820E+00	7.092E-02	1.275E-02	0.000E+00	2.195E-01	6.594E-01

20040 = TARGET 1000Z+A (if A=0 then elemental)

1001 = PROJECTILE 1000Z+A

Aver. lab emission energies for A&lt;5 projectiles in MeV:

Energy	neutron	proton	deuteron	triton	helium3	alpha	gamma
5.000E+00	0.000E+00	1.464E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	3.267E+00
6.000E+00	0.000E+00	2.242E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	3.196E+00
7.000E+00	0.000E+00	3.061E+00	0.000E+00	0.000E+00	0.000E+00	1.492E+00	3.068E+00
8.000E+00	0.000E+00	3.719E+00	0.000E+00	0.000E+00	0.000E+00	2.277E+00	2.916E+00
9.000E+00	0.000E+00	4.087E+00	0.000E+00	0.000E+00	0.000E+00	3.164E+00	2.823E+00
1.000E+01	0.000E+00	4.433E+00	0.000E+00	0.000E+00	0.000E+00	4.055E+00	2.822E+00
1.100E+01	0.000E+00	4.726E+00	0.000E+00	0.000E+00	0.000E+00	4.895E+00	2.901E+00
1.200E+01	0.000E+00	4.822E+00	0.000E+00	0.000E+00	0.000E+00	5.495E+00	2.978E+00
1.300E+01	0.000E+00	4.669E+00	0.000E+00	0.000E+00	0.000E+00	6.121E+00	3.002E+00
1.400E+01	0.000E+00	4.568E+00	0.000E+00	0.000E+00	0.000E+00	6.306E+00	2.982E+00
1.500E+01	0.000E+00	4.558E+00	1.131E+00	0.000E+00	0.000E+00	5.855E+00	2.941E+00
1.600E+01	3.907E-01	4.772E+00	2.070E+00	0.000E+00	0.000E+00	5.576E+00	2.872E+00
1.700E+01	9.662E-01	5.032E+00	3.057E+00	0.000E+00	0.000E+00	5.592E+00	2.825E+00
1.800E+01	1.384E+00	5.278E+00	3.844E+00	0.000E+00	0.000E+00	5.782E+00	2.734E+00
1.900E+01	1.713E+00	5.508E+00	4.282E+00	0.000E+00	0.000E+00	6.043E+00	2.625E+00
2.000E+01	1.932E+00	5.687E+00	4.710E+00	0.000E+00	0.000E+00	6.329E+00	2.587E+00
2.200E+01	2.647E+00	6.193E+00	5.781E+00	9.743E-01	0.000E+00	6.757E+00	2.529E+00
2.400E+01	3.328E+00	6.626E+00	6.859E+00	2.745E+00	0.000E+00	7.139E+00	2.528E+00
2.600E+01	3.851E+00	6.979E+00	8.096E+00	3.864E+00	0.000E+00	7.423E+00	2.547E+00
2.800E+01	4.366E+00	7.307E+00	9.288E+00	4.783E+00	0.000E+00	7.567E+00	2.566E+00
3.000E+01	4.826E+00	7.644E+00	1.045E+01	5.805E+00	0.000E+00	7.541E+00	2.545E+00
3.500E+01	5.959E+00	8.599E+00	1.319E+01	8.268E+00	0.000E+00	7.878E+00	2.369E+00
4.000E+01	7.217E+00	9.621E+00	1.612E+01	1.046E+01	0.000E+00	8.414E+00	2.312E+00
4.500E+01	8.269E+00	1.056E+01	1.896E+01	1.231E+01	0.000E+00	8.775E+00	2.330E+00
5.000E+01	9.185E+00	1.135E+01	2.183E+01	1.387E+01	0.000E+00	9.059E+00	2.327E+00
5.500E+01	1.006E+01	1.203E+01	2.421E+01	1.520E+01	0.000E+00	9.302E+00	2.322E+00

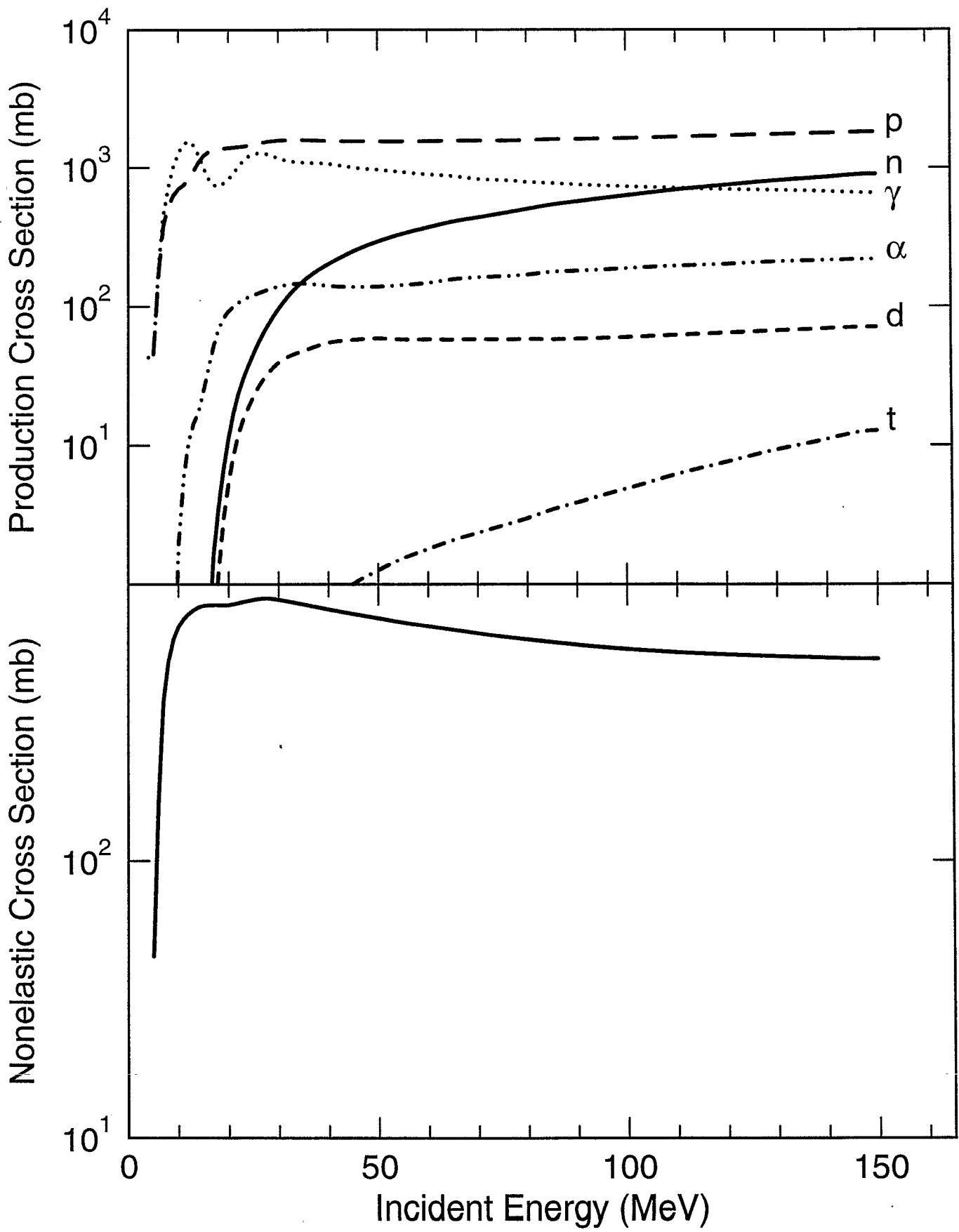
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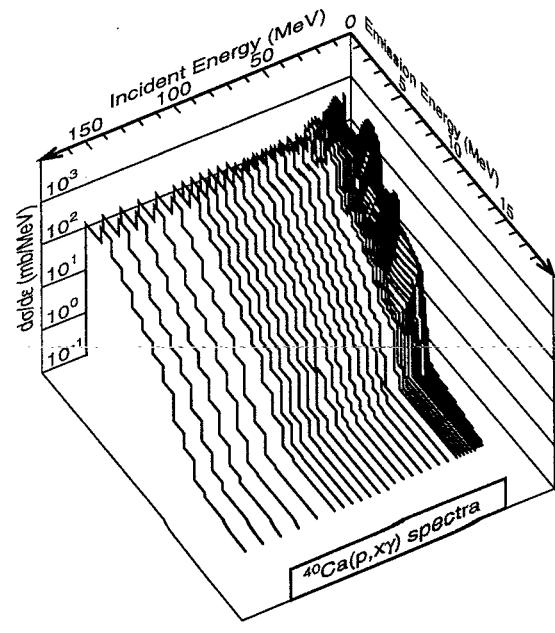
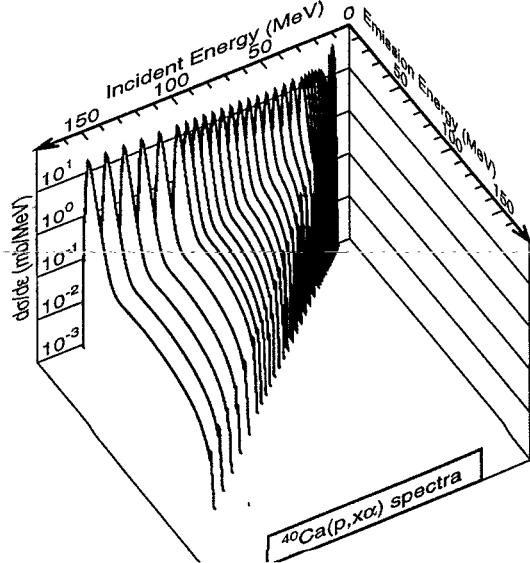
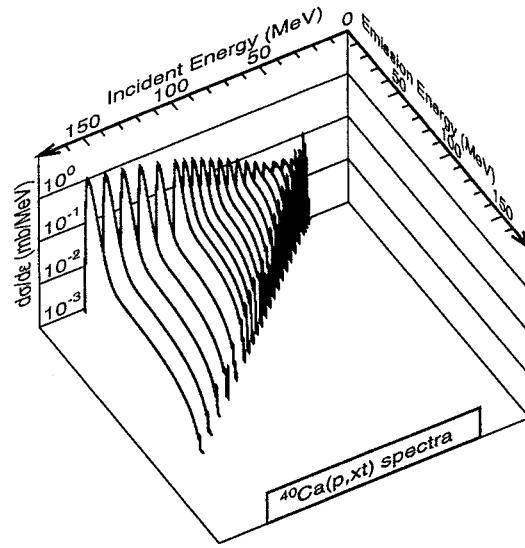
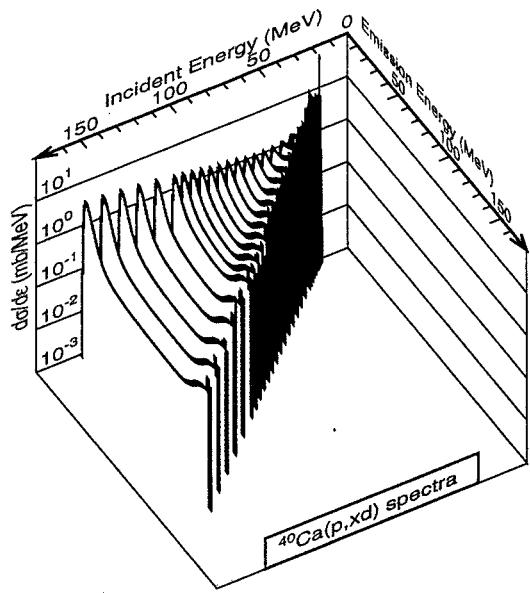
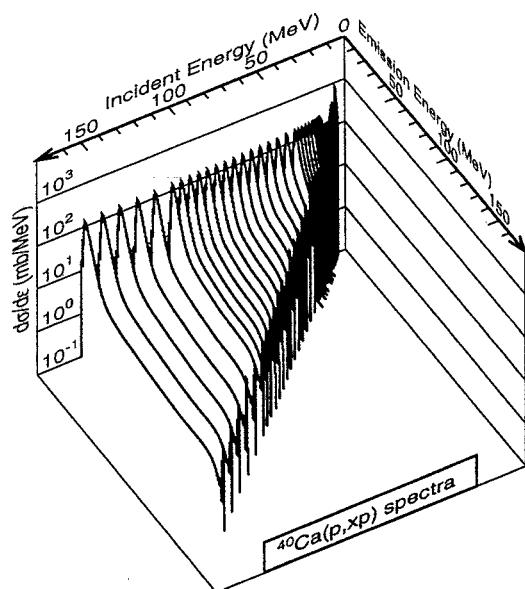
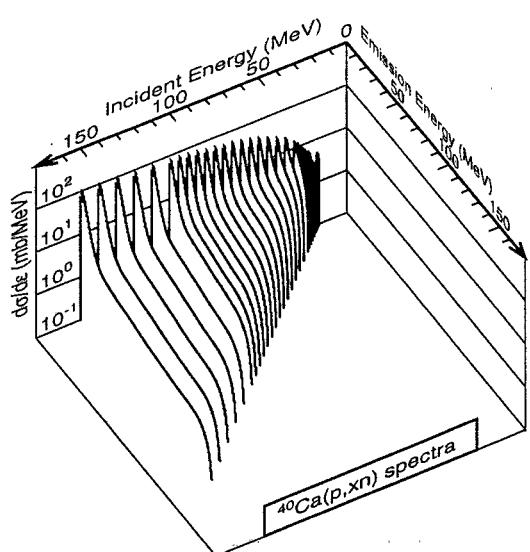
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6.000E+01	1.085E+01	1.267E+01	2.667E+01	1.626E+01	0.000E+00	9.521E+00	2.326E+00
6.500E+01	1.136E+01	1.318E+01	2.858E+01	1.681E+01	0.000E+00	9.712E+00	2.331E+00
7.000E+01	1.205E+01	1.379E+01	3.077E+01	1.729E+01	0.000E+00	9.861E+00	2.389E+00
7.500E+01	1.264E+01	1.442E+01	3.245E+01	1.756E+01	0.000E+00	1.012E+01	2.404E+00
8.000E+01	1.308E+01	1.499E+01	3.426E+01	1.762E+01	0.000E+00	1.029E+01	2.390E+00
8.500E+01	1.337E+01	1.542E+01	3.486E+01	1.722E+01	0.000E+00	1.045E+01	2.381E+00
9.000E+01	1.380E+01	1.597E+01	3.622E+01	1.699E+01	0.000E+00	1.062E+01	2.391E+00
9.500E+01	1.421E+01	1.651E+01	3.739E+01	1.666E+01	0.000E+00	1.077E+01	2.387E+00
1.000E+02	1.462E+01	1.703E+01	3.838E+01	1.629E+01	0.000E+00	1.088E+01	2.364E+00
1.100E+02	1.534E+01	1.798E+01	3.921E+01	1.536E+01	0.000E+00	1.119E+01	2.334E+00
1.200E+02	1.619E+01	1.906E+01	3.985E+01	1.470E+01	0.000E+00	1.151E+01	2.341E+00
1.300E+02	1.696E+01	2.001E+01	3.920E+01	1.406E+01	0.000E+00	1.176E+01	2.342E+00
1.400E+02	1.782E+01	2.099E+01	3.885E+01	1.359E+01	0.000E+00	1.200E+01	2.338E+00
1.500E+02	1.880E+01	2.204E+01	3.796E+01	1.327E+01	0.000E+00	1.225E+01	2.319E+00

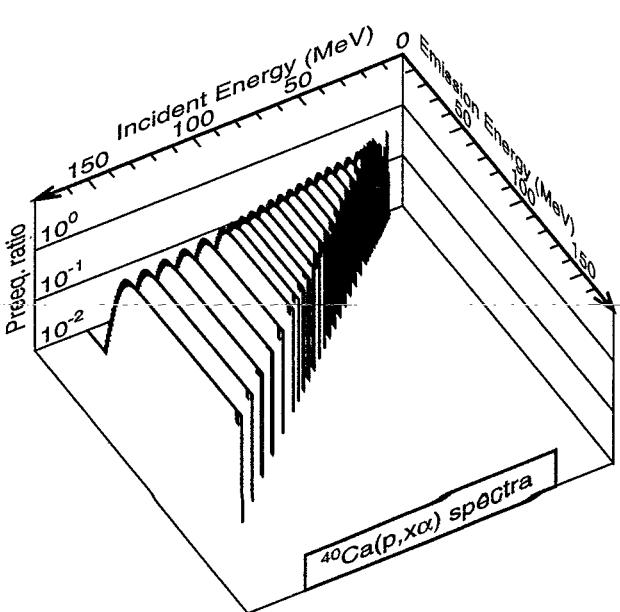
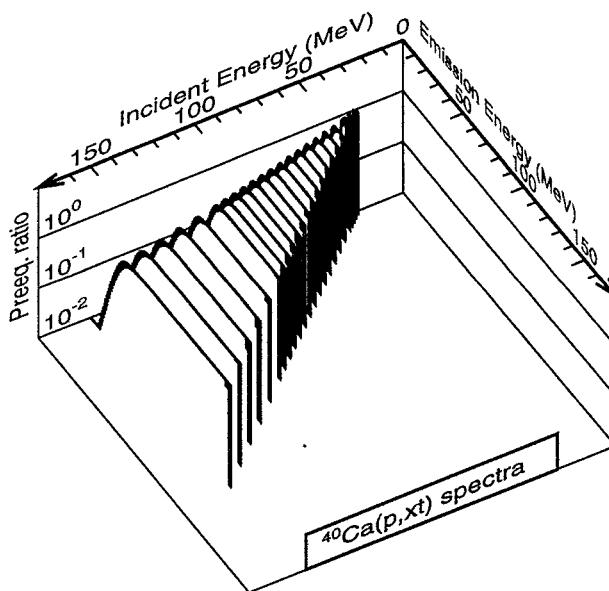
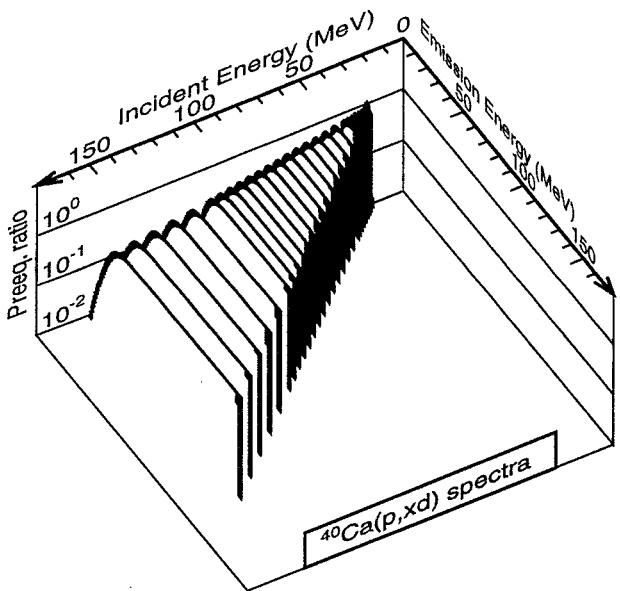
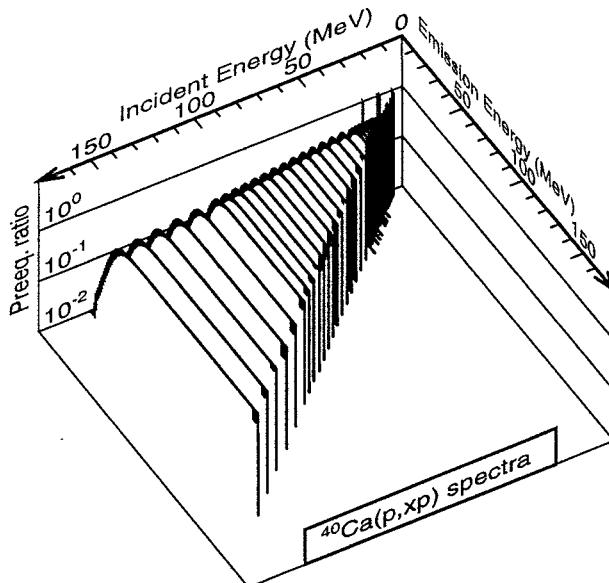
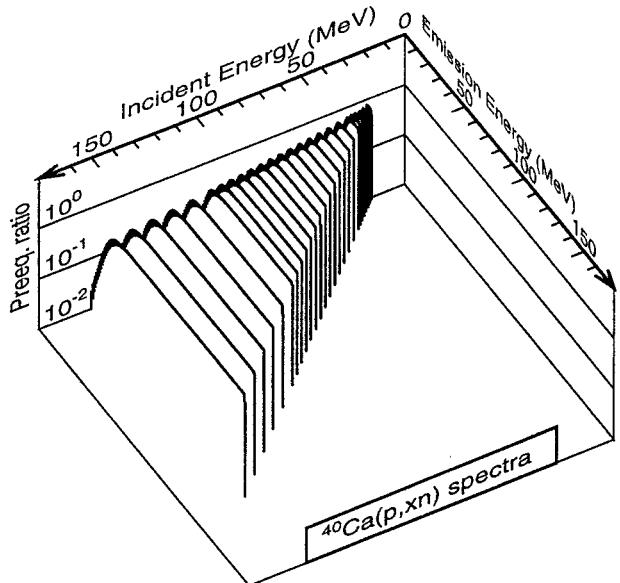
$p + {}^{40}\text{Ca}$  nonelastic and production cross sections



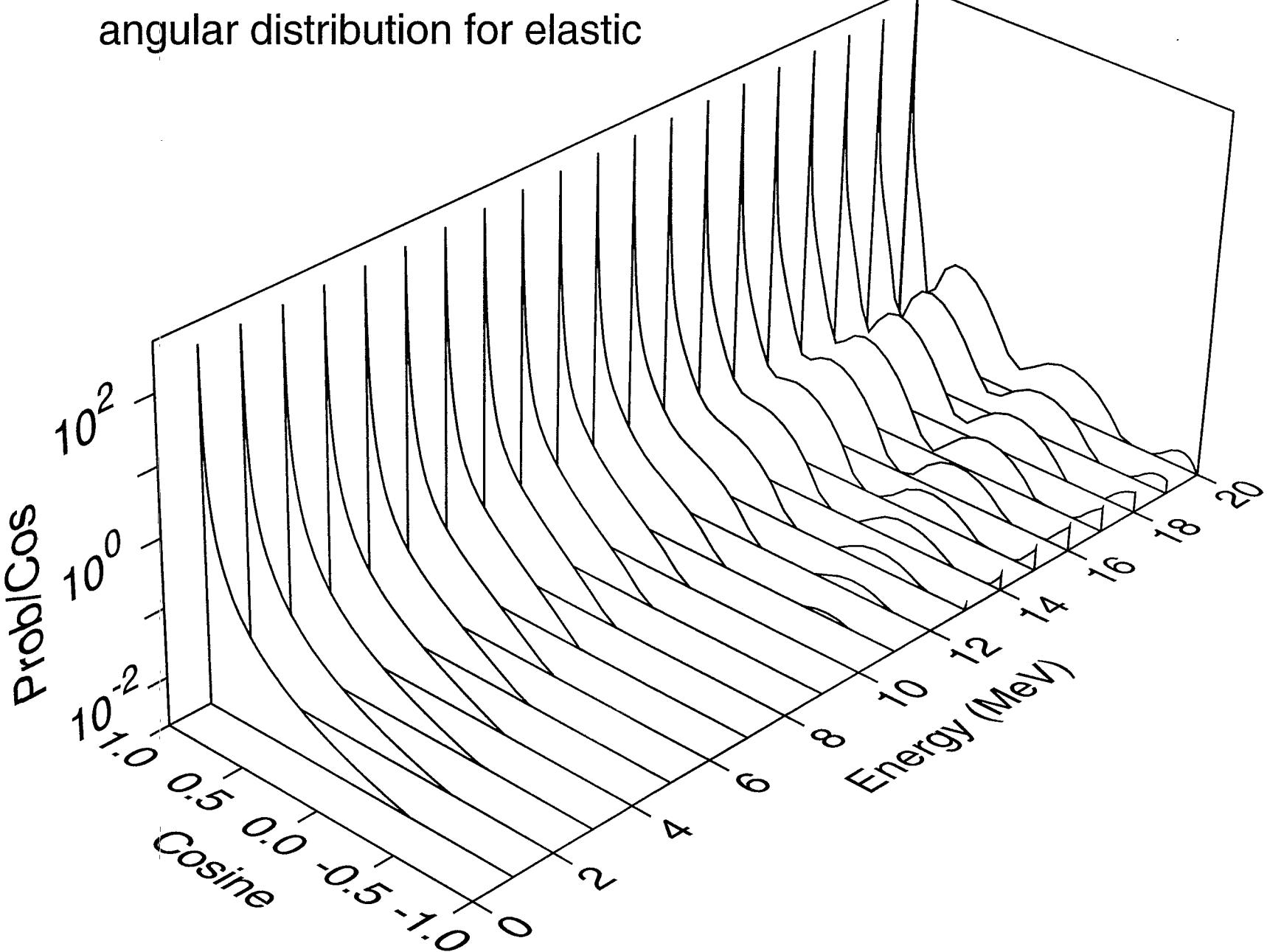
# $p + {}^{40}\text{Ca}$ angle-integrated emission spectra



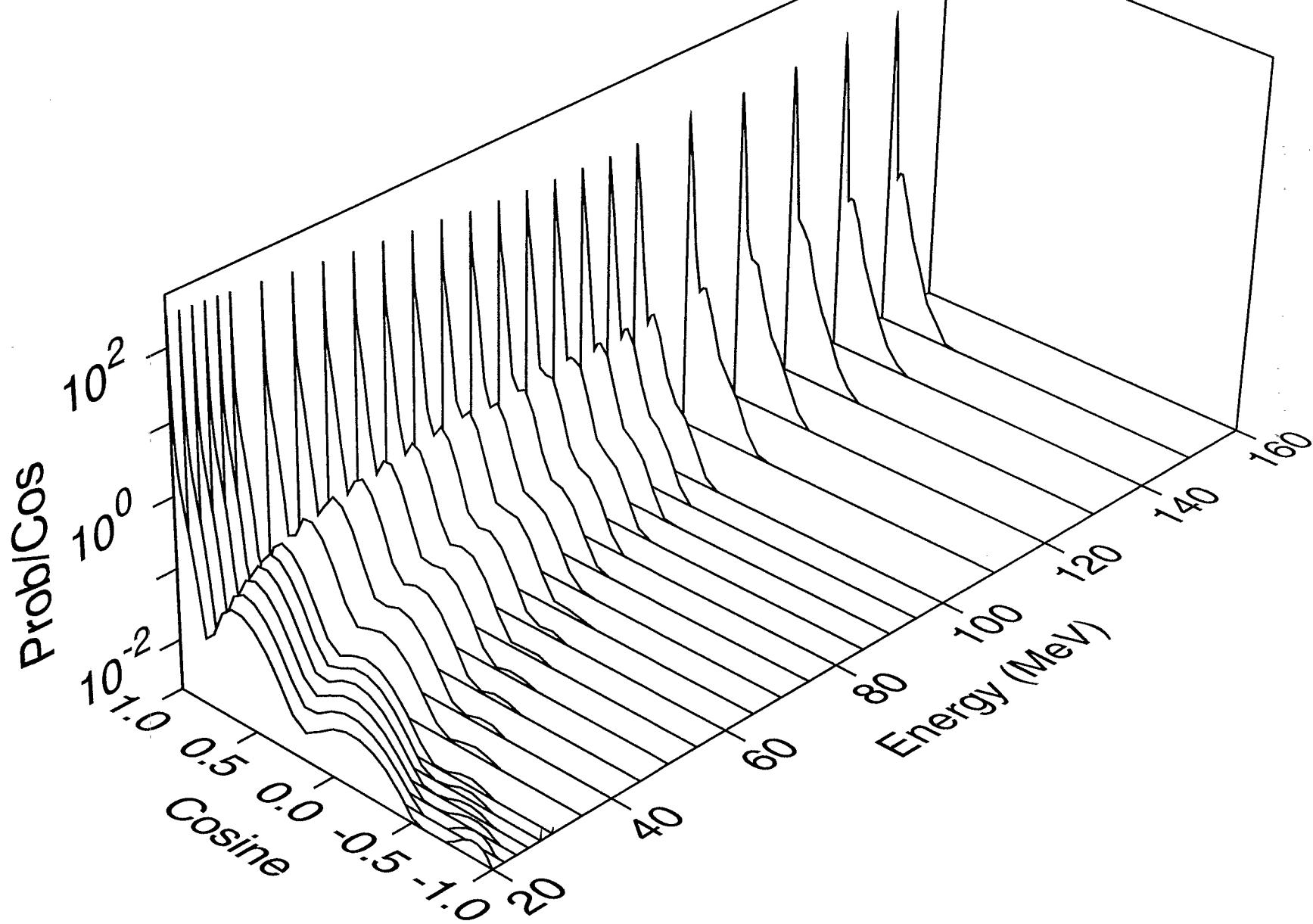
# $p + {}^{40}\text{Ca}$ Kalbach preequilibrium ratios



20-CA-40 APT LA150 NJOY 97.45X MCNPX  
angular distribution for elastic



20-CA-40 APT LA150 NJOY 97.45X MCNPX  
angular distribution for elastic



20-CA-40 APT LA150 NJOY 97.45X MCNPX

Heating

